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X64956

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ARTILLERY PREDICTOR

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FIG. 1

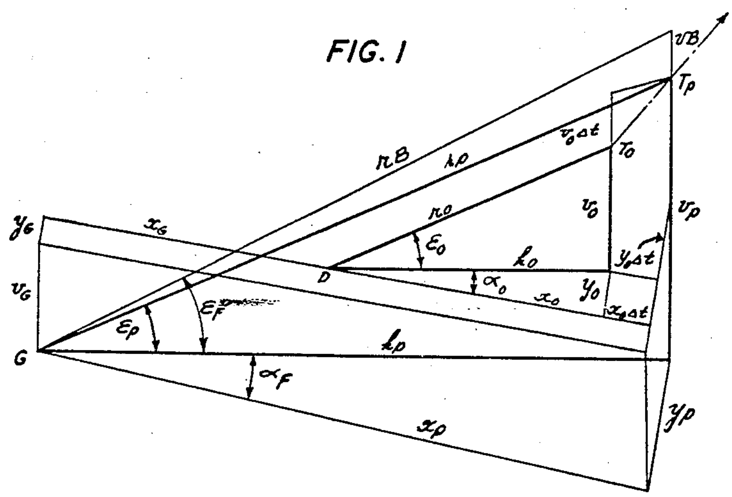

FIG. 2

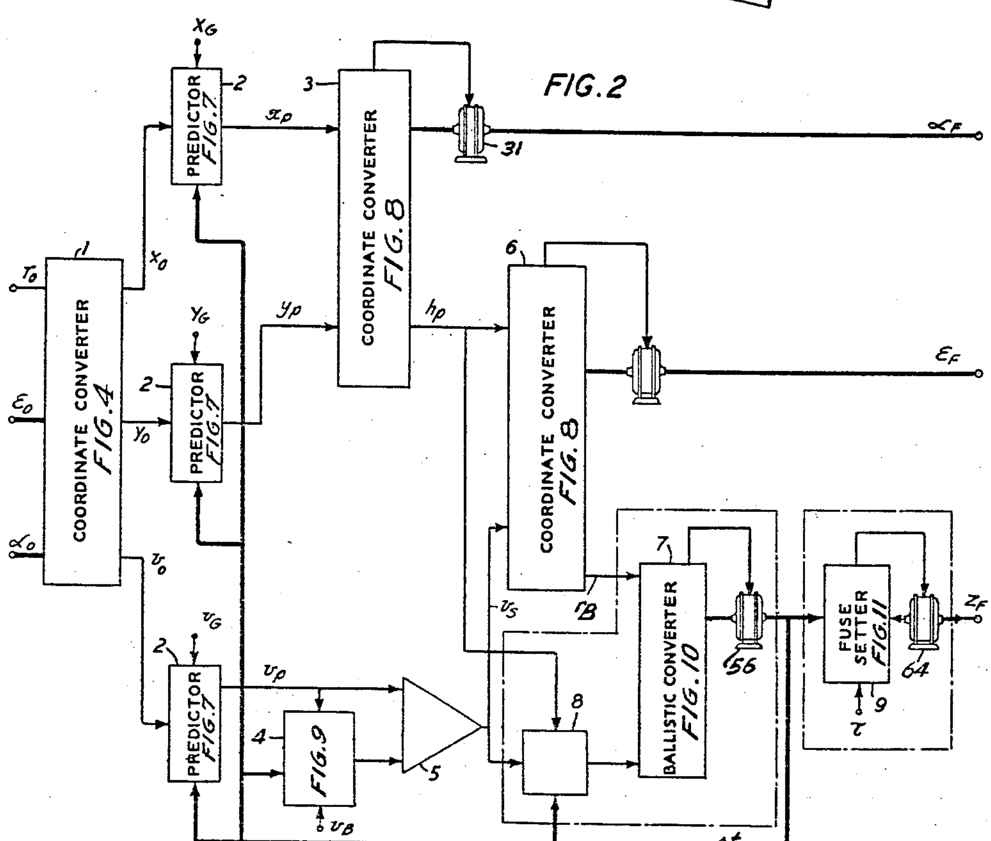

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FIG. 3

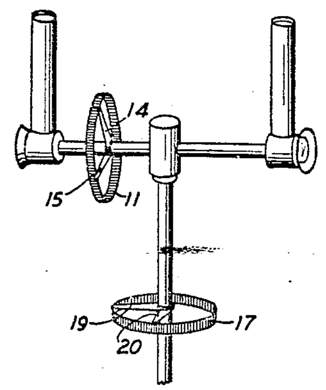

FIG. 4

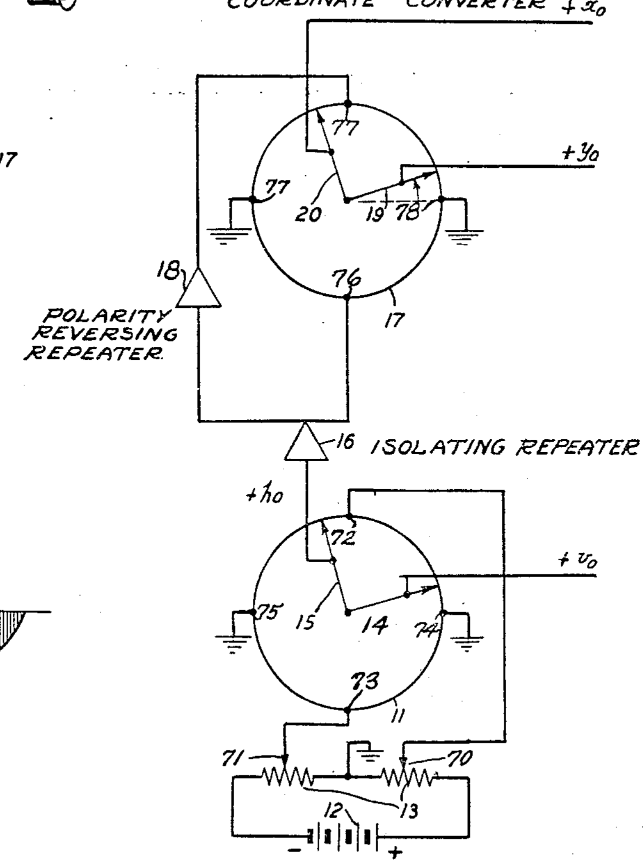

FIG. 5

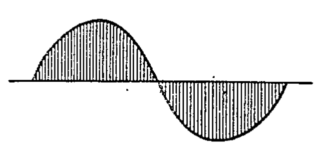

FIG. 6

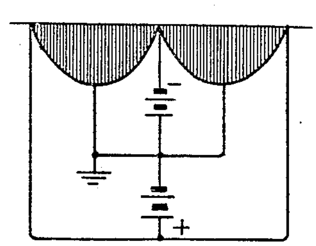

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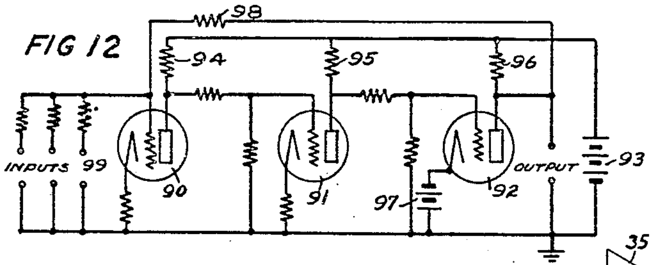
FIG 12



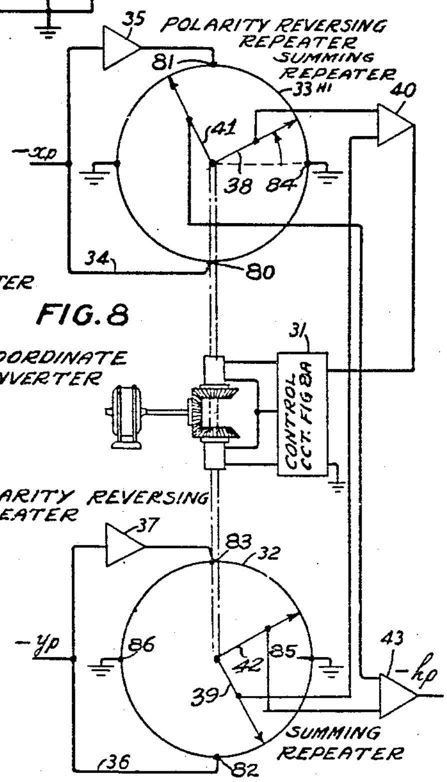


FIG. 8

COORDINATE CONVERTER

FIG. 7

PREDICTOR

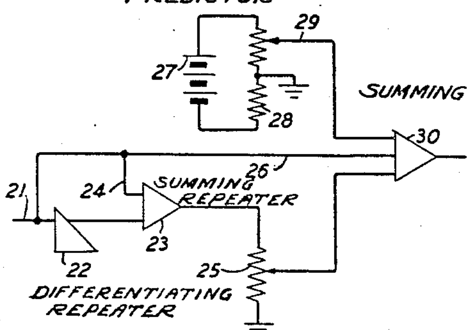
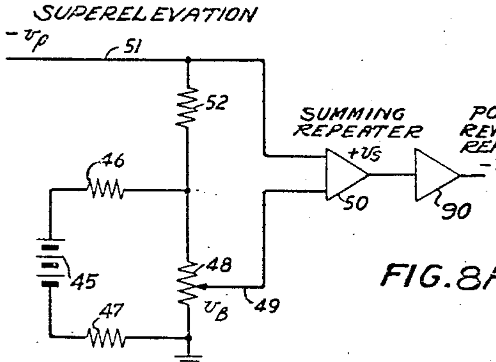


FIG. 9

SUPERELEVATION



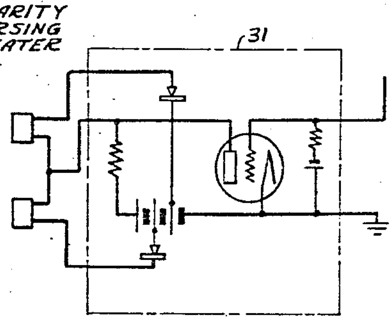


FIG. 8A

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FIG. 10

BALLISTIC CONVERTER

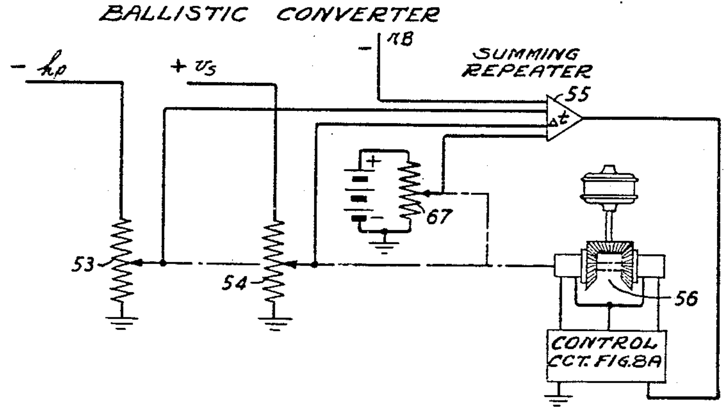
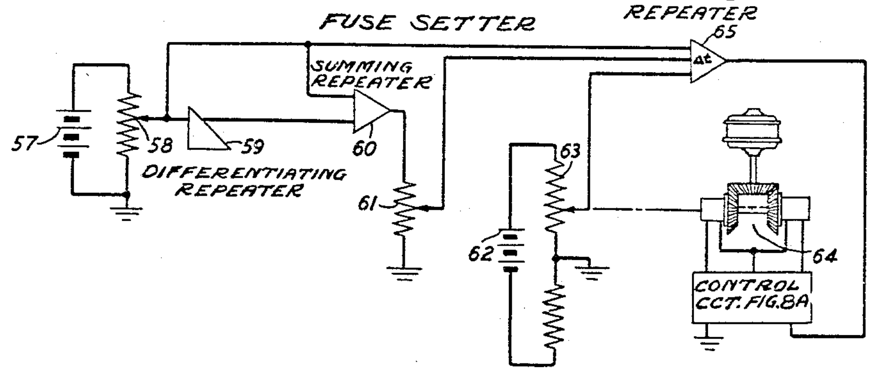


FIG. 11

FUSE SETTER



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UNITED STATES PATENT OFFICE

2,408,081

ARTILLERY PREDICTOR

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Application May 1, 1941, Serial No. 391,438

9 Claims. (Cl. 235—61.5)

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This invention relates to control of artillery fire and particularly to electrical means for computing the values to be used in controlling fire against rapidly moving targets.

The object of the invention is to compute for a gun the fuse range and the angles of elevation and azimuth which will direct the fire of the gun to the predicted position of a moving target.

A feature of this invention is a method of making predictions of the future position of the target which has only one major feedback involved in the prediction. This feedback consists in the use of the time of flight Δt, which depends upon the predicted position, in the calculations of the increments which are to be added to present position data to give the future position. It has been the practice of many director designers to use not only this type of feedback but to use also formulae as a basis of their predictions which involve directly the time of flight Δt, the present position coordinates and the future position coordinates. This introduces multiple feedback loops which have detrimental effects on the stability of the instrument.

Another feature of the invention is the conversion by electrical means of measurements taken in polar coordinates into the corresponding rectangular coordinates.

Another feature of the invention is the derivation, from the measurements taken at the point of observation of electrical voltages proportional to the rectangular coordinates of the predicted position of the target at the gun.

Another feature of the invention is the correction of the vertical coordinate of the predicted position of the target for the superelevation of the gun.

A further feature of the invention is, by electrical means to derive a motion proportional to the time of flight of the shell from the gun to the predicted position of the target and to use this motion to control those factors in the ranging of the gun which vary with the time of flight of the shell.

Another feature of the invention is to derive from the motion proportional to the time of flight of the shell a motion proportional to the appropriate setting of the fuse for such time of flight.

A further feature of the invention is the calculation of all predicted values and corrections

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by means of a null method so that fluctuations of the energizing voltages used in making the calculations will not introduce errors in the results provided all the voltages used rise and fall together. It is a further property of this method that all energizing voltages are made to depend on a single voltage source so that they all fluctuate only as this primary source fluctuates.

A further feature of the invention is the conversion of the rectangular coordinates of the predicted position of the target as seen at the gun into the angles of azimuth and elevation to be applied to the gun.

Further features of the invention will be apparent from the following description, combined with the drawings in which:

Fig. 1 gives the geometry of the director, target and gun;

Fig. 2 is a schematic drawing of the complete system;

Fig. 3 shows the mechanism for tracking the target;

Fig. 4 diagrammatically shows the mechanism for converting polar coordinates into voltages proportional to the rectangular coordinates;

Figs. 5 and 6 show a type of potentiometer card forming an element of the device in Fig. 2;

Fig. 7 diagrammatically shows apparatus for modifying a rectangular coordinate of the present position of the target to produce a voltage representing the predicted position of the target with respect to the gun;

Fig. 8 diagrammatically shows apparatus for converting voltages proportional to the rectangular coordinates into quantities proportional to the corresponding polar coordinates;

Fig. 8A schematically shows the control circuit of Fig. 8;

Fig. 9 diagrammatically illustrates apparatus for modifying the coordinate of height to add into predicted data a correction for the superelevation of the gun;

Fig. 10 diagrammatically shows apparatus for deriving a voltage proportional to the time of flight of the shell and of moving a series of devices proportionally to this time;

Fig. 11 diagrammatically shows apparatus for converting the time of flight of the shell into a motion proportional to the fuse setting; and

Fig. 12 schematically shows a repeater for summing up a plurality of voltages.

In Fig. 1, T_0 represents the target, D the director or point of observation, and G represents the gun. By means of any known form of range finder the slant distance r_0 between the director and target is measured. Also by any suitable instrument, such as the tracker shown in Fig. 3, the angle of azimuth α_0 between some assumed axis and the target is measured and the angle of elevation ϵ_0 between the horizontal at the director and the target is also measured. Let the origin of the rectangular coordinates be at the director, let the azimuth angle α_0 be measured from any desired line which is considered as the positive X axis, and let x_G, y_G and v_G be the rectangular coordinates of the gun with respect to the director.

The rectangular coordinates of the target from the director are

$$\begin{aligned} x_0 &= r_0 \cos \epsilon_0 \cos \alpha_0 \\ y_0 &= r_0 \cos \epsilon_0 \sin \alpha_0 \\ v_0 &= r_0 \sin \epsilon_0 \end{aligned} \qquad (1)$$

The horizontal range

$$h_0 = r_0 \cos \epsilon_0 \qquad (2)$$

When expressed in rectangular coordinates, the position of the target with respect to the director can be converted into the position of the target with respect to the gun by algebraic addition of the coordinates with proper attention to the algebraic signs.

$$\begin{aligned} x &= x_0 + x_G \\ y &= y_0 + y_G \\ v &= v_0 + v_G \end{aligned} \qquad (3)$$

Next consider the increments to these rectangular coordinates which must be added to obtain the coordinates of the predicted position of the target. These increments are given by

$$\begin{aligned} \Delta x &= \dot{x}\Delta t \\ \Delta y &= \dot{y}\Delta t \\ \Delta v &= \dot{v}\Delta t \end{aligned} \qquad (4)$$

where Δt is the time of flight of the shell from the gun to the predicted position of the target, and this time is as yet undetermined.

An advantage gained through use of rectangular coordinates for making the predictions is that the increments computed from observations made at the director can be used without modification as the increments to be added at the gun to give the true predicted position of the target.

Thus the rectangular coordinates of the predicted position of the target with respect to the gun are

$$\begin{aligned} x_p &= x_0 + x_G + \dot{x}_0\Delta t \\ y_p &= y_0 + y_G + \dot{y}_0\Delta t \\ v_p &= v_0 + v_G + \dot{v}_0\Delta t \end{aligned} \qquad (5)$$

In Fig. 2 a voltage r_0 proportional to the reading of the range finder, and angular indications respectively proportional to the angles of azimuth and elevation are supplied to the coordinate converter **1** which converts these indications into electrical voltages proportional to the rectangular coordinates x_0, y_0 and v_0 of the present position of the target as seen from the director or point of observation. The arrow-headed light lines in Fig. 2 represent electrical voltages supplied from one part of the system to another, the arrow-headed heavy lines in Fig. 2 represent mechanical motions, of which only the motion proportional to Δt, the time of flight of the shell, is fed back to control the magnitudes of the voltages in the system.

These voltages are supplied to prediction mechanisms where they are differentiated with respect to time to give voltages which, when multiplied by the time of flight Δt will give the respective increments. These increments are added to the original coordinates together with the gun coordinates to give the rectangular coordinates of the predicted position with respect to the gun.

The voltages proportional to x_p and y_p are supplied to the coordinate converter **3** which sets itself to indicate the angle α_f, the azimuth angle at the gun corresponding to the predicted position of the target, and also produces a voltage proportional to the horizontal distance from the gun to the predicted position of the target.

The voltage proportional to the predicted vertical height of the target with respect to the gun is combined in the network **5** with a correction voltage depending upon the superelevation to be applied to the gun, obtained from the corrector **4**.

This voltage v_s as corrected, together with the voltage proportional to the horizontal projection of the target obtained from the coordinate converter **3**, is supplied to the coordinate converter **6** which sets itself to indicate the angle of elevation ϵ_f of the gun at the instant of firing, and produces a voltage proportional to the slant distance r_b from the gun to the superelevated position of the target.

Voltages respectively proportional to h_p, v_s and r_b are supplied to the ballistic converter **7** which sets itself to indicate the time of flight Δt from the gun to the predicted position of the target, and at the same time, as indicated by the line joined to the output of this converter, adjusts those elements of the predictors **2**, the network **4** and the network **8** which are proportional to the time of flight.

The ballistic converter also delivers to the fuse setting network **9**, a voltage proportional to the time of flight of the shell which is corrected in this network for the dead time required to prepare the gun, set the fuse and fire the gun, and then converted into a motion proportional to the setting of the fuse. This motion may be transmitted in any desired manner to the members of the gun crew to indicate the setting of the fuse.

When this system is used in connection with guns, such as machine guns, using solid ammunition, the fuse setting network **9** may be omitted.

The coordinate converter **1** is shown in greater detail in Fig. 4. One of the main elements of this device is a potentiometer arrangement **11** which gives a voltage representing a complete sinusoidal function. In Fig. 5 is shown a curve varying in accordance with the familiar sinusoidal function. Such a function has a positive value in the first two quadrants and a negative value in the last two quadrants of a complete revolution.

Since physical resistances have only positive values it is necessary to use polarities of the voltages across the potentiometers to get the change in sign of the function. Thus the complete function is represented by a resistance shaped as shown in Fig. 6 with the voltages across the two halves of the resistance having opposite polarity. The resistor may be made of suitable resistance wire or material formed of some resistance composition, or may be wound around a flat strip of some insulating material which is subsequently formed into a circle, the insulation on the wire on the top edge of the strip being removed, and a wiper arranged when rotated to rub over these bare wires. The circuit may conveniently be

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arranged so that the potentiometer is connected to ground at the points where the sinusoidal function passes through zero. The shape of the flat strip of insulating material may be determined by a consideration of the voltage to be produced at the wiper.

Let

w=width of card varying with angle α,
R=resistance per unit length of wire,
n=turns of wire per unit length of card,
R_m=total resistance of wire for whole card.

Then resistance per unit length of card is $2nRw$, and the resistance to the wiper at angle α is

$$R_\alpha=\int_0^\alpha 2nRw.d\alpha$$

and

$$w=\frac{1}{2nR}\cdot\frac{dR\alpha}{d\alpha}$$

But, the voltage selected by the wiper is to vary with sin α, the maximum value R_m of the resistance of the potentiometer representing the maximum value, unity, of sin α.

Thus

$$w=\frac{1}{2nR}\cdot\frac{d(R_m \sin \alpha)}{d\alpha}=\frac{R_m}{2nR}\cdot\cos \alpha$$

The width of the card and the resistance per unit length of the winding vary with the rate of change of sin α, that is, cosine α. As shown in Fig. 4 the circularly arranged potentiometer **11**, is grounded at diametrically opposite points **74**, **75**. A voltage from the source **12** is applied to a potentiometer **13** grounded at its mid-point. Two wipers **70**, **71** moved in accordance with the readings of the range finder produce voltages, respectively positive and negative, proportional to the range. These voltages are applied to diametrically opposite points **72**, **73** of the potentiometer **11**. The wipers **14** and **15** bearing upon the potentiometer **11** are moved in accordance with the angle of altitude of the target as observed. If desired, the potentiometer **11** may conveniently be mounted on a tracking mechanism as shown in Fig. 3 and the wipers **14** and **15** may be directly moved by the altitude tracking telescope, or any desired intermediary may be used such as gearing, a flexible shaft or Selsyn motors, to produce an angular movement of the wipers proportional to the angle of altitude moved by the telescope.

With the potential applied to the potentiometer **11**, as shown, zero angle being at the point **74** and the wiper **14** rotating counter-clockwise, the wiper **14** will have, during one revolution, a potential with respect to ground, varying in sinusoidal fashion from zero, to positive maximum, to zero, to negative maximum back to zero. The potential of this wiper with respect to ground thus varies as a positive sine. If another wiper be located 180 degrees from the wiper **14**, during one revolution of these two wipers, the second wiper will have a potential with respect to ground varying in sinusoidal fashion from zero, to negative maximum, to zero, to positive maximum back to zero. The potential of this second wiper will thus vary as what may be termed a negative sine. The same variation will also be produced if the wiper **14** rotates in a counter-clockwise direction from a zero angle at the point **75** of the potentiometer. If the wiper **14** rotates in a clockwise direction from a zero angle at the point **74**, the potential of the wiper **14** with respect to ground will vary with what may be termed a negative sine, and if the wiper **14** rotates in a clockwise direction from a zero angle at the point **75**, the potential of the wiper **14** with respect to ground will vary as a positive sine. Also, if the polarities of the potentials applied to the points **72**, **73** be reversed, the sign of the function will be reversed. Thus, the sign of the function may be reversed by a reversal of the direction of the wiper, a reversal of the direction of rotation, a reversal of the point selected as zero angle, or a reversal of the polarity of the applied potential. When the wiper **14** is rotating counter-clockwise, the wiper **15** leads the wiper **14** by an angle of 90 degrees, thus the wiper **15** will have a potential with respect to ground varying as a positive cosine. The factors which reverse the sign of the functional variation of potential of the wiper **14** will also reverse the sign of the functional variation of potential of the wiper **15**. Further, if the cosine wiper leads the sine wiper by 90 degrees, the cosine function has the same sign as the sine function; if the cosine wiper lags behind the sine wiper by 90 degrees, the cosine function has the opposite sign to the sine function.

With zero degrees at the point **74**, and counter-clockwise rotation, the positive wiper **14** will have a potential with respect to ground proportional to the range multiplied by the positive sine of the angle of elevation of the present position of the target, that is, to v_0, the vertical height of the target above the horizontal plane at the point of observation. The wiper **15** is placed at right angles to the wiper **14** and selects a voltage proportional to the cosine of the angle of elevation, thus this wiper will have a positive potential with respect to ground proportional to the product of the range multiplied by the positive cosine of the angle of elevation, that is, the horizontal distance from the point of observation to the projection of the present position of the target on the horizontal plane. This voltage is supplied through a repeater **16**, which may conveniently be of unity voltage gain, and acts to electrically isolate the wiper **15** and reverse the polarity of the potential from wiper **15**, to one diametrical point **76** of the sinusoidally varying potentiometer **17** and through a polarity reversing repeater **18** to the other diametrical point **77** of the potentiometer **17**. The repeater **18** reverses the polarity of the voltage supplied to the potentiometer **17** and preferably should have a voltage gain of unity. The other diametrical points of the potentiometer **17** are grounded as discussed hereinabove. The wipers **19** and **20** of the potentiometer **17** are moved in a counter-clockwise direction from the point **78**, in accordance with the angle of the azimuth telescope shown in Fig. 3, when tracking the target. The potentiometer **17** may, if desired, be mounted directly on the tracking mechanism and the wipers **19** and **20** may be directly attached to the azimuth tracking telescope, or they may be moved in accordance with the movement of this telescope by means of any convenient mechanism, such as gearing, flexible shafting, Selsyn motors or other devices.

The voltage from the repeater **16** is proportional to the voltage between the wiper **15** and ground, that is, the product of the range multiplied by the cosine of the angle of elevation, thus the voltage of the wiper **19** with respect to ground will be proportional to the product of the range multiplied by the positive cosine of the angle of elevation and multiplied by the positive sine of the angle of azimuth, that is, to the rectangular coordinate y_0.

The wiper **20** is at right angles to the wiper **19** which, as explained hereinabove in connection with the wiper **15**, has the effect of multiplying the voltage applied to the potentiometer **17** by the cosine of the angle of rotation of the wiper **20**, thus the voltage of this wiper with respect to ground will be proportional to the product of the range multiplied by the positive cosine of the angle of elevation multiplied by the positive cosine of the angle of azimuth, that is, to the coordinate x_0.

The converter shown in Fig. 4 has thus received an electrical voltage proportional to the range from the director to the target and angular indications of the angles of elevation and azimuth measured by the tracking telescopes and has converted these indications into positive voltages with respect to ground proportional to the rectangular coordinates x_0, y_0 and v_0 of the present position of the target with respect to the director.

The predictors **2** may be of the type shown in Fig. 7. The voltage corresponding to the coordinate is supplied over the wire **21** to a circuit **22** which will produce the differential or time derivative of the input voltage. These differentiators may be of any desired form, such as those shown in U. S. Patents 1,311,283, July 29, 1919, R. C. Mathes, or 1,315,539, September 9, 1919, J. R. Carson, or, preferably, of the type disclosed in U. S. application Serial No. 391,332 to H. G. Och and K. D. Swartzel, Jr., filed of even date herewith. The differentiator disclosed in United States application Serial No. 391,332 includes a repeater of the type shown in Fig. 12 with a capacitor, connected from a tap in the feedback resistor **98** to ground, to produce the differentiating action. The input lead **21**, Fig. 7, is connected to an input resistor, similar to the resistor **99** of Fig. 12. The output of the differentiator **22** will contain a component varying as the differential of the input voltage, that is, the time derivative of the particular rectangular coordinate, and this voltage is supplied to the summing repeater **23**. The summing repeater **23**, as shown in Fig. 12, may be a reverse feedback amplifier having three amplifiers **90**, **91**, **92**. As the voltages to be summed up may be direct voltages, or of low frequency, the coupling between stages may be of the type shown in United States Patent 1,751,527, March 25, 1930, H. Nyquist. The cathodes are heated by conventional means, not shown. The source **93** supplies power to the anode circuits through the anode coupling resistors **94**, **95**, **96**. The first two stages may be self-biased by the conventional resistors. The circuit elements associated with the amplifier **92** are adjusted so that, in the absence of an applied signal, the voltage of the source **93** is wholly lost in the resistor **96** and the anode of the amplifier **92** is at ground potential, so that no voltage is produced across the output circuit. A source of voltage **97**, having the negative pole connected to the cathode of amplifier **92** and the positive pole grounded, maintains the anode current of amplifier **92**. A large value of reverse feedback is supplied, through resistor **98** to the input of the repeater. The large value of feedback reduces the apparent input impedance of the amplifier **90** to a small value; thus a plurality of voltages may be connected to the input of the amplifier **90** through individual resistors, such as resistor **99**, without interaction. Because of the large value of feedback, the amplification of any input voltage is substantially independent of the voltage amplification of the amplifier, and depends only on the ratio of the resistances of the feedback resistor **98**, and the input resistor, such as resistor **99**. As the repeater shown in Fig. 12 has an odd number of stages, the input voltage will be reversed in polarity. Thus a repeater of this type may be used for the polarity reversing repeaters **18**, **35**, **37**, and, as all simple thermionic repeaters are inherently unilateral devices, this repeater may also be used as the isolating repeater **16**. In many cases the output of the differentiator will contain a component varying directly in accordance with the input voltage applied to the differentiator in addition to the voltage varying as the differential of the input voltage. To eliminate this undifferentiated component, sufficient voltage is supplied by the wire **24** to the summing repeater **23** in such phase as to cancel out the effect of the undifferentiated component in the amplifier **23** and give across the potentiometer **25** a voltage varying only with the differential of the input voltage. The wiper of the potentiometer **25** is moved by the shaft of the servo-motor shown in Fig. 10 in accordance with the time of flight Δt from the gun to the predicted position of the target, thus the voltage between the wiper of the potentiometer **25** and ground varies in accordance with a factor having the form $\dot{x}_0 \Delta t$. The voltage supplied by the wire **26** will be proportional to x_0. A source of current **27** is supplied to a potentiometer **28** having the mid-point of the potentiometer connected to ground. The wiper **29** is adjusted on the potentiometer **28** to give a voltage having a magnitude and polarity proportional to the coordinate from the point of observation to the gun, that is, a coordinate of the character x_G. The voltages from the potentiometers **25** and **28** and from the wire **26** are summed up in the summing repeater **30**. The output of this repeater **30** will be a voltage proportional to $x_0+\dot{x}_0\Delta t+x_G$, that is, to x_p, the rectangular component of the predicted position of the target with respect to the gun. Similar components are summed up for the y_p coordinates and the v_p coordinates.

In the present system, the potentials corresponding to the coordinates x_0, y_0, v_0 are positive. The differentiator **22** reverses the polarity of the differential, but the polarity of the differential is again reversed by the summing repeater **23**. Thus, the potentials respectively corresponding to the quantities x_0, $\dot{x}_0\Delta t$, x_G or y_0, $\dot{y}_0\Delta t$, y_G or v_0, $\dot{v}_0\Delta t$, v_G are all positive. The summing repeater **30** reverses these polarities, thus, x_p, y_p and v_p are negative potentials.

The coordinate converter **3** may be of the type disclosed in Fig. 8. From Equation 1 by analogy, we may write,

$$x_p=h_p \cos \alpha_f$$
$$y_p=h_p \sin \alpha_f \qquad (6)$$

Multiplying both sides of the first equation by $\sin \alpha_f$, and the second equation by $\cos \alpha_f$ and rearranging, we get

$$x_p \sin \alpha_f - h_p \cos \alpha_f \sin \alpha_f = 0$$
$$y_p \cos \alpha_f - h_p \sin \alpha_f \cos \alpha_f = 0 \qquad (7)$$

Subtracting these equations, we get

$$x_p \sin \alpha_f - y_p \cos \alpha_f = 0 \qquad (8)$$

As described hereinabove, the coordinate converter shown in Fig. 4 produces voltages proportional to the rectangular coordinates x_0, y_0, v_0 of the present position of the target with respect to the director. Each of these volages is modified by a predictor of the type shown in Fig. 7, to produce a voltage proportional to one of the rectangular coordinates x_p, y_p, v_p of the predicted position of the target with respect to the gun. When controlled by the voltages proportional to x_p and y_p, the comparison device shown in Fig. 8 will rotate the wipers of the potentiometers **32** and **33** through an angle equal to α_f, see Equation 8, the azimuthal angle at the gun between the x_p axis and the predicted position of the target. The device shown in Fig. 8 may conveniently be a modification of the device disclosed in United States Patent 2,003,913, June 4, 1935, E. C. Wente, and comprises a motor geared to two pinions rotatably mounted upon a common shaft. Magnetic clutches are associated with each pinion, so that, when a clutch is energized the respective pinion will drive the common shaft. The operation of the magnetic clutches is controlled by a comparison circuit **31**. Voltages supplied to this circuit are compared by the circuit with a standard, and if there is a deviation from the standard, the circuit **31** causes the operation of one of the magnetic clutches to rotate the shaft. As the voltages supplied to the comparison circuit **31** are derived from potentiometers having their wipers rotated by the shaft, the shaft will rotate, moving the wipers on the potentiometers, until the voltages from the wipers supplied to the circuit **31** equal the standard. The circuit **31** then releases the operated clutch and the shaft and wipers, displaced through an angle proportional to the deviation from standard, come to rest. The potentiometers **32**, **33** have windings, varying in resistance in accordance with a sinusoidal function, similar to the windings of potentiometers **11** and **17**. The negative voltage varying with the x_p coordinate is supplied through the wire **34** to one diametrical point **80** of the winding of the potentiometer **33**, and through a polarity reversing repeater **35** to the other diametrical point **81** of the winding of the potentiometer **33**. The function of the repeater **35** is to reverse the polarity of the voltage, in a manner similar to the operation of an inverter tube, thus the repeater **35** should have an odd number of stages and an over-all voltage gain of unity. In a similar manner a negative voltage varying with the y_p coordinate is applied through the wire **36** to one point **82**, and through the reversing repeater **37** to a diametrically opposite point **83** of the winding of the potentiometer **32**. The diametrically opposite intermediate points of the windings of the potentiometers **32**, **33** are grounded.

The potentiometers **32**, **33** have windings of the type shown in Fig. 6, and, as explained hereinabove in connection with potentiometers **11**, **17**, due to the reversal of polarity of the voltage supplied to one half of the winding, the voltage drop around the complete winding of potentiometer **32** or **33** varies as a complete sine function. The wipers **38**, **41** and **39**, **42** rotate counter-clockwise from a zero angle at the points **84**, **85**. The wipers **38** and **42** will thus have positive voltages above ground proportional to the positive sine of the angle of rotation. A positive cosine function is identical with a positive sine function which it leads by a right angle, thus the wiper **41** will have a positive voltage proportional to the positive cosine of the angle of rotation. Displacing a cosine function through two right angles reverses the sign of the function, thus the wiper **39**, which is diametrically opposite to the wiper **41** will have a negative voltage proportional to the negative of the cosine of the angle of rotation. The angle of rotation of the wipers will be continually adjusted by the comparison circuit **31** until a balanced condition is attained. The wiper **38** will have a voltage with respect to ground proportional to x_p sine αf, and the wiper **39** will have a voltage with respect to ground proportional to $-y_p \cos \alpha f$. The voltages from the wipers **38** and **39** are added in the device **40**, which is of the type shown in Fig. 12 and supplies a voltage proportional to $x_p \sin \alpha f - y_p \cos \alpha f$ to the control circuit **31**, which energizes the appropriate clutch to cause the rotation of the shaft moving the wipers **38** and **39** to such a position that this voltage is reduced to zero. The wipers **38**, **39**, **41**, **42** have thus been rotated through the angle αf.

Equation 8 has as solutions

$$\alpha_f = \tan^{-1}\frac{y}{x} \qquad (9)$$

which is a multiple valued function. If α_{f0} represents the smallest angle that will satisfy (9) then $\alpha_{f0} \pm n\pi$, $n=1, 2, 3, \ldots$ are also solutions. However there are only two distinct points on the circle represented in this set of solutions i. e., those corresponding to $n=0$ and $n=1$. It can be shown that if the servo motor is connected so as to correct for deviations in the neighborhood of the desired root then the second root becomes unstable. If the brushes happen to be set on this root when the circuit is energized it will remain at that position only long enough for a small deviation to appear. This deviation will be amplified and will cause the motor to move the brush but it will move away from the unstable root and come to rest on the correct solution 180 degrees away. Thus in spite of the fact that the equations have two significant solutions the device will come to rest on only the desired one and there is no ambiguity in the solution.

From Equations 1 and 2 it follows

$$x_p = h_p \cos \alpha_f \qquad (10)$$
$$y_p = h_p \sin \alpha_f$$

Multiplying the first equation by $\cos \alpha_f$ and the second equation by $\sin \alpha_f$, we get

$$x_p \cos \alpha_f = h_p \cos^2 \alpha_f \qquad (11)$$
$$y_p \sin \alpha_f = h_p \sin^2 \alpha_f$$

Thus

$$x_p \cos \alpha_f + y_p \sin \alpha_f - h_p = 0$$

Thus by placing a second wiper **41** on the potentiometer **33** at 90 degrees to the wiper **38** and a second wiper **42** on the potentiometer **32** also at 90 degrees to the wiper **39** we may derive from the potentiometer **33** a positive voltage varying with $x_p \cos \alpha_f$ and from the potentiometer **32** a positive voltage varying with $y_p \sin \alpha_f$ and these voltages may be summed up and reversed in polarity in the repeater **43** to give a negative voltage proportional to the horizontal range from the gun to the predicted position of the target. In Equation 8 we have a sine term minus a cosine term, whereas in Equation 11 we have a sine term plus a cosine term. To correctly indicate this difference the wiper **41** on the potentiometer **33** is placed 180 degrees from the corresponding wiper **39** on the potentiometer **32** so as to produce this required reversal of sign in the two equations. The motion proportional to α_f, which is the angle of azimuth to be applied to the gun, may be communicated to the guns in any desired manner.

In Fig. 1, due to the curvature of the trajectory, the gun is elevated, not to the elevation angle E_p of the predicted position T_p of the target, but to the quadrant elevation, or firing elevation angle E_F, to a point above the target. The principal force tending to curve the trajectory is the attraction of gravity, which produces a displacement proportional to the square of the time interval during which it acts upon the shell. The friction of the air also affects the curvature of the trajectory, and this effect is found to be proportional to the predicted height of the target. Thus, the superelevation

$$v_B=\frac{1}{2}g(\Delta t)^2(1+Kvp)$$

where K is a factor determined from the firing tables for the particular gun and ammunition, and g is the acceleration due to gravity.

In Fig. 9 a source of voltage **45** is applied through attenuators **46** and **47** to the winding of potentiometer **48**. The potentiometer **48** is wound to have a resistance varying with the quadratic function in accordance with the variation of the superelevation of the gun with the time of flight of the shell. A wiper **49** is moved over this potentiometer in accordance with the time of flight of the shell from the gun to the predicted position of the target. The attenuators **46** and **47** reduce the voltage from the source **45** so that the voltage **49** will have the proper scale. The voltage from the wiper **49** is supplied to the summing repeater **50**. A negative voltage from the predictor, Fig. 7, proportional to the coordinate v_p is supplied by the wire **51** also to the summing repeater **50**. The voltage from the wire **51** is also applied through the resistance **52** to the potentiometer **48** and supplies a voltage proportional to Kvp in accordance with the required function of superelevation. The summing repeater **50** will have a positive output voltage proportional to the apparent vertical component v_s due to the superelevation of the gun. The output voltage of the repeater **50** is versed in polarity by the repeater **90** to produce a negative voltage proportional to $-v_s$.

The negative voltage from the coordinate converter **3** proportional to h_p, the horizontal projection of the predicted position of the target with respect to the gun, and the negative voltage from the summing repeater **90** of Fig. 9, proportional to v_s, the vertical component of the superelevated position of the gun, are supplied to the coordinate converter **6**, similar to the converter shown in Fig. 8. The negative voltage proportional to h_p has the same sign as the negative voltage proportional to x_p and the negative voltage proportional to v_s has the same sign as the negative voltage proportional to y_p. With zero angle at points **84**, **85** and counter-clockwise rotation, the wiper **38** selects a voltage proportional to $+h_p \sin \epsilon_f$ and the wiper **39** selects a voltage proportional to $-v_s \cos \epsilon_f$. The voltages selected by the wipers **38**, **39** are algebraically added in the repeater **40**, and the difference is supplied to the circuit **31** which controls the magnetic clutches to rotate the shaft moving all the wipers until the difference is reduced to zero and the wipers have been moved to the angle ϵ_f. The voltages from the wipers **41** and **42** respectively proportional to $+h_p \cos \epsilon_f$ and $+v_s \sin \epsilon_f$ are added, and reversed in sign, in the repeater **43**, to produce an output voltage proportional to $-r_b$, which is approximately equal to $-r_p$, the range from the gun to the predicted position of the target.

From the firing tables for a typical gun and ammunition, the time of flight Δt, of the shell was found to be closely, but not exactly, proportional to the slant distance r_b. By combining with the value of r_b small corrections proportional to h_p and v_s a value exactly proportional to Δt is obtained.

The time of flight of the shell, Δt, will depend upon the length of the trajectory and the speed of the shell along the trajectory. To a first approximation, the length of the trajectory may be assumed to be equal to r_p, and, if the speed S of the shell were constant, $s\Delta t=r_p$. But as the speed of the shell varies from one trajectory to another, the time of flight will depend, not only on r_p but also on ϵ_f. The exact relationships between the time of flight, slant range and quadrant elevation are given in the firing tables for the gun used. From a study of these tables the following empirical relationship was deduced: $f_1(\Delta t)=h_f \cos \epsilon_f+V_s \sin \epsilon_f-h_f f_2(\Delta t)+V_s f_3(\Delta t)$. But, $h_f \cos \epsilon_f+V_s \sin \epsilon_f=r_b$, and $h_f=h_p$, thus $f_1(\Delta t)-r_b-h_p f_2(\Delta t)+V_s f_3(\Delta t)=0$. The functions f_1, f_2 and f_3 are substantially linear, and may be exactly determined from the firing tables for any particular gun.

As shown in Fig. 10, the voltage h_p from the coordinate converter **3**, shown in Fig. 8, is supplied to the potentiometer **53**, the voltage v_s from the network **5** is supplied to the potentiometer **54**. The wipers of these potentiometers are moved by the shaft of the servo-motor **56** in accordance with Δt, the time of flight of the shell, and the voltages produced on these wipers are summed up in the summing repeater **55**, together with the voltage r_b from the coordinate converter **6**, shown in Fig. 8, and a comparison voltage from the wiper of potentiometer **67**. The output voltage of the repeater **55** is supplied to a servo motor **56** of the type described in connection with Fig. 8, and this servo motor adjusts the wipers of the potentiometers **53**, **54** and **67** to maintain the output voltage of the repeater **55** constant. The wipers of the potentiometers **25** in the predictors, Fig. 7, of the potentiometer **48** in the superelevator, Fig. 9, are all mounted to be driven by the shaft of the servo motor **56** and adjusted simultaneously with the adjustment of the wipers of the potentiometers **53** and **54** in Fig. 10.

In Fig. 11 a source **57** supplies voltage to the winding of the potentiometer **58**. The wiper of the potentiometer **58** is controlled by the servo motor **56** of the ballistic corrector **7**, Figs. 2 and 10, to move in accordance with Δt, the time of flight of the shell from the gun to the predicted position of the target. The voltage selected by the wiper of potentiometer **58** is continuously proportional to the present time of flight, that is, assuming the gun were fired at the present instant, the time which the shell would take to reach the target. But, after the fuse is cut, the shell must be loaded into the gun, the breechblock closed and the gun fired. The time interval T from the present time till the gun is fired is known as the dead time. The fuse number Z is proportional to the value which the time of flight will have after the lapse of the dead time. The continuously varying values of the present time of flight are extrapolated over the dead time by Taylor's series. Thus, if Z be the fuse number and T the dead time, then

$$Z(\Delta t+T)=Z(\Delta t)+\frac{d}{dt}Z(\Delta t)\cdot T$$

The voltage on the wiper **58** is supplied to a differentiator **59** of the type described in connection with Fig. 7. The output of the differentiator **59** together with a compensating voltage from the wiper **58** is supplied to the summing repeater **60**, and the output of the repeater **60**, varying in accordance with the differential of the time of flight, is applied to the potentiometer **61**. The wiper of the potentiometer **61** is adjusted in accordance with the arbitrary assumed dead time to lay the gun, set the fuse and fire the gun. A source **62** supplies voltage to the balanced potentiometer **63**. The wiper of the potentiometer **63** is moved by a servo motor **64** similar to the servo motors previously described. A voltage from the wiper of the potentiometer **58**, a voltage from the wiper of the potentiometer **61** and a voltage from the wiper of the potentiometer **63** are summed up in the summing repeater **65** and supplied to the servo motor **64**, which will adjust the wiper of the potentiometer **62** to balance the voltages. As the resistance of the winding of the potentiometer **63** is varied in accordance with the empirical relationship between the time of flight of the shell and the units used to indicate the setting of the fuse, the position of the wiper of the potentiometer **63** will indicate the setting to be applied to the fuse and this information may be transmitted in any desired manner to the gun, or may control some power transmitting mechanism, such as a Selsyn motor or a servo motor driving an automatic fuse setting machine or mechanism. The summing repeaters **23**, **30**, **40**, **43**, **50**, **55**, **60** and **65** may all be of the type shown in Fig. 12.

What is claimed is:

1. In an artillery director, means directly controlled by observation of a target for producing a first voltage with respect to ground proportional to the slant distance from an observation point to said target, means moved in accordance with the directly observed angles of elevation and azimuth of said target with respect to said point and an arbitrary axis, means for deriving from said first voltage and said angular motions other voltages with respect to ground proportional to the rectangular coordinates of said target with respect to said point, thermionic means for deriving from said coordinate voltages other voltages with respect to ground proportional to the rates of change of said coordinates, means for selecting from said rate voltages other voltages with respect to ground proportional to the predicted increments in said coordinates, thermionic means for algebraically adding said coordinate and said increment voltages, and electromechanical means controlled by the sums of said voltages to move proportionally to the angles of elevation and azimuth of the predicted position of said target and to produce a voltage proportional to the slant distance to said target.

2. In an artillery director, means directly controlled by observation of a target for producing a first voltage with respect to ground proportional to the slant distance from an observation point to said target, means moved in accordance with the directly observed angles of elevation and azimuth of said target with respect to said point and arbitrary axes, means for deriving from said first voltage and said angular motions other voltages with respect to ground proportional to the rectangular coordinates of said target with respect to said point and said axes, means for deriving from said coordinate voltages other voltages with respect to ground proportional to the predicted increments in said coordinate voltages during a predicted time interval, thermionic means for algebraically adding said coordinate voltages and said increment voltages and electromechanical means controlled by the sums of said voltages to move proportionally to the angles of elevation and azimuth and to produce a voltage proportional to the slant distance to the predicted position of said target.

3. In a system for directing a shell from a gun to a moving target, means directly controlled by observations of said target for producing voltages with respect to ground proportional to the coordinates of the present position of said target with respect to said gun, adjustable electrical means for deriving from said present position voltages other voltages with respect to ground proportional to the coordinates of the future position of said target with respect to said gun after the lapse of the time of flight of said shell from said gun to the future position of said target, and electromechanical means controlled by said future position voltages to move proportionally to the elevation and azimuth angles of the future position of said target and the time of flight of said shell, said electrical means being adjusted only by said time of flight means.

4. In a system for directing a shell from a gun to a target, electrical means controlled by observation of the present position of said target forming a source of a first voltage with respect to ground proportional to the predicted elevation of said target, a source of a second voltage, a resistor connected to said first source of voltage, a potentiometer having a grounded winding varying in resistance with a quadratic function connected across said second source, the ungrounded end of said winding being connected to said resistor and a brush adjusted to select a voltage proportional to the linear height of the superelevated line of said gun above said target, and thermionic means for adding the voltages from said first source and said brush to produce a voltage proportional to the superelevated height of the line of fire to said target.

5. In a system for indicating the time of flight of a shell from a gun to a target, a source of a first voltage with respect to ground proportional to the horizontal distance from said gun to the projection of said target, a first potentiometer having a grounded winding connected to the source of said first voltage and a first brush, a source of a second voltage with respect to ground proportional to the superelevated height of the line of fire to said target, a second potentiometer having a grounded winding connected to the source of said second voltage and a second brush, a source of a third voltage with respect to ground proportional to the slant distance to the superelevated point on said line of sight vertically above said target, a source of a fourth voltage, a third potentiometer having a grounded winding connected across the source of said fourth voltage and a third brush, thermionic means for algebraically adding the voltages from said three brushes and from said third source, and a motor connected to said thermionic means and controlled by the sum of said voltages to move said three brushes to make the sum of said voltages zero, whereby the rotation of said motor is proportional to the time of flight of said shell.

6. In a system for directing a shell from a gun to a target, computing elements continuously controlled by observation of said target including motor means rotated in accordance with the present time of flight of the shell from the gun to a predicted position of the target, a source of a first voltage, a first potentiometer having a grounded winding connected across said source and a first brush moved by said motor to select a second voltage proportional to the present time of flight, first thermionic means connected to said first brush to produce a third voltage proportional to the rate of change of said second voltage, resistance means connected to said first thermionic means to fractionate said third voltage in proportion to the estimated time interval from the present time to the firing of the gun, second thermionic means connected to said first brush and said resistance means, a motor connected to said second thermionic means, a source of a fourth voltage, a second potentiometer having a grounded winding connected across the source of said fourth voltage and a second brush connected to said second thermionic means and adjusted by said motor to make the output of said thermionic means zero, whereby the position of said second brush is proportional to the fuse number corresponding to the time of flight of said shell at the time of firing of said gun.

7. In a system for directing a shell from a gun to target, computing means continually controlled by observations of said target to produce a first voltage proportional to the present time of flight of the shell from the gun to a predicted position of the target, electrical means connected to said computing means to produce a second voltage proportional to the rate of change of said first voltage, means connected to said electrical means fractionating said second voltage to produce a third voltage proportional to the estimated time to load and fire the gun, a motor, thermionic means having an input circuit connected to said computing means and said fractionating means and an output circuit connected to said motor for adding said first and said fractionated voltages to produce a fourth voltage proportional to the corrected time of flight of said shell, a source of a fifth voltage, a potentiometer having a winding varying in resistance with the functional relationship between time of flight and fuse number connected across the source of said fifth voltage and a brush connected to the input circuit of said thermionic means and rotated by said motor to make the output voltage of said thermionic means zero, whereby the rotation of said brush is proportional to the fuse number of said shell.

8. In a coordinate converter, a source of voltage, a network connected to said source having one grounded terminal and two free terminals, adjustable means in said network for impressing on said free terminals equal voltages of opposite polarity with respect to ground proportional to the hypotenuse of a right triangle, a winding formed in two sections, each section varying in resistance with a sinusoidal function and shaped to an arc of a circle, the ends of each of said sections being respectively connected to said free terminals and the points of maximum variation of resistance of said sections being grounded, two insulated wipers supported at right angles respectively in contact with the sections of said winding and mechanism for rotating said wipers about the center of said circle proportionally to a base angle of said triangle to respectively select voltages with respect to ground proportional to the sides of said triangle.

9. In a coordinate converter, a source of voltage, a network connected to said source having one grounded terminal and two free terminals, adjustable means in said network for impressing on said free terminals equal voltages of opposite polarity with respect to ground proportional to the slant distance from a point to an object, a first winding formed in two sections, each section varying in resistance with a sinusoidal function and shaped to an arc of a first circle, the ends of each of said sections being respectively connected to said free terminals and the points of maximum variation of resistance of said sections being grounded, a first and a second insulated wiper supported at right angles respectively in contact with the sections of said first winding, mechanism for rotating said first and second wipers about the center of said first circle proportionally to the angle of elevation of said object with respect to said point to respectively select voltages with respect to ground proportional to the horizontal distance from said point to the projection of said object and the height of said object, polarity reversing thermionic means, a second winding formed in two sections, each section varying in resistance with a sinusoidal function and shaped to an arc of a second circle, said first wiper being connected directly to one end of each of said sections and through said polarity reversing means to the other end of said sections, a third and a fourth insulated wiper supported at right angles respectively in contact with the sections of said second winding, mechanism for rotating said third and fourth wipers about the center of said second circle proportionally to the azimuth angle between an arbitrary axis and the vertical plane containing said point and said object to respectively select voltages with respect to ground proportional to the horizontal rectangular coordinates of the projection of said object with respect to said point.

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